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IRAS 05436–0007 and the Emergence of McNeil's Nebula

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ABSTRACT

We present a study of McNeil's Nebula, a newly appeared reflection nebula in the L1630 cloud, together with photometry and spectroscopy of its source. New IR photometry compared to earlier 2MASS data shows that the star has brightened by about 3 magnitudes in the near-infrared, changing its location in a J-H/H-K′ diagram precisely along a reddening vector. A Gemini NIRI K-band spectrum shows strong CO-bandhead emission and Brγ is in emission, indicative of strong accretion. A Gemini GMOS optical spectrum shows only a red, heavily veiled continuum, with Hα strongly in emission and displaying a pronounced P Cygni profile, with an absorption trough reaching velocities up to 600 km s^{-1}. This implies significant mass loss in a powerful wind. However, no evidence is found for any shocks, as commonly seen in collimated outflows from young stars. Apparently the eruption has dispersed a layer of extinction and this, together with the intrinsic brightening of the IRAS source, has allowed an earlier outflow cavity to be flooded with light, thus creating McNeil's Nebula.

Subject headings: stars: formation — stars: pre–main-sequence — Reflection nebulae — ISM: individual(McNeil's Nebula) — stars: variables: other

1. Introduction

Wide-field photographic and CCD images have documented the presence of numerous small compact reflection nebulae in star-forming dark clouds. Such nebulae may possibly represent a transitional stage in which a young star goes from being an embedded infrared source to a visible T Tauri star or Herbig Ae/Be star. This process is widely believed to involve powerful bipolar outflow activity, as reflected in the morphology of the nebulae, which are often cometary, with the partially embedded star illuminating an outflow cavity. When observed over longer time-scales, such small reflection nebulae are often found to vary in brightness and occasionally in illumination pattern. Perhaps the earliest known example is NGC 2261, which reflects light from the young star R Mon and was found to vary by Hubble (1916). More recently, Cohen et al. (1981) demonstrated the variability of the fan-shaped nebula emanating from PV Cephei. At some stage, the outflow activity of a star for the first time punches a hole in its surroundings, suddenly allowing a beam of light to sweep across the surroundings. Subsequent eruptions in the source will again flood the outflow channel with light. The emergence of the nebula Re 50 in the Lynds 1641 cloud near the embedded source IRAS 05380–0728 was documented by Reipurth & Bally (1986). Another case may have been the nebula IC 430 in L1641, which at present is quite small, but at the end of the 19th century appears to have been a very large and much brighter object (Pickering 1890; Strom & Strom 1993).

2. Observations

The observations presented below were taken on the "Frederick C. Gillett" Gemini North Telescope[1], on Mauna Kea, Hawaii on UT dates February 03 (near-IR) and 14 (optical), 2004. The near-IR imaging and spectroscopy was acquired with the facility imager/spectrometer, NIRI, using the f/6 camera giving an image scale on the Aladdin InSb 1024x1024 detector of 0.116"/pixel. Images in J, H and K′ were obtained in total on-source integration times of 3.6 seconds (0.18 seconds, 10 coadds, two spatial positions) in each filter. The data were calibrated using similar observations of the UKIRT faint standard stars FS113, 119 and 135. The spectroscopic data were acquired using a 0.5" wide long-slit and K-band grism with a

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total on-source integration time of 60 seconds (30 seconds, 1 coadd, two spatial positions) resulting in a spectrum with resolving power ∼780 covering the wavelength region 2.05-2.45 microns. Telluric feature correction was performed using observations of the A0 V star HIP28056. The optical data were acquired using the facility optical multi-object spectrometer, GMOS-N. Images in the GMOS Sloan g', r', i' and z' filters were obtained with exposure times of 60 seconds and 10 seconds, the shorter exposure time being used to give unsaturated images of the young star. The GMOS spectrum was a 5 min exposure obtained using the R831 grating, 0.5" wide long-slit, and a central wavelength of 5800 Å resulting in a spectrum covering the wavelength range 4800-6800 Å at a resolving power of R∼4500. Infrared images were obtained of the eruptive star at the UH 2.2m telescope through an R-band filter (5 min exposure) on Feb 1, 2004 and through a narrowband H_2 2.12 μm filter (20 min exposure) on Feb 14, 2004 UT.

3. Pre-outburst Observations

On January 23, 2004, McNeil (2004)[2] discovered the presence of a bright nebula more than an arcminute in extent south-west of M78 in the L1630 cloud, a nebula that was not seen on any of the blue or red POSS-I, POSS-II and UKSTU sky atlas plates taken between 1951 and 1991. McNeil's Nebula is clearly cometary-shaped, with a highly reddened, dust-obscured star at its apex. Subsequent examination of recent images obtained in the fall of 2003 suggests that McNeil's Nebula first appeared in late November 2003 (Briceño et al. 2004; McNeil, priv. comm.). However, Mr. John Welch of Phoenix, Arizona, kindly brought our attention to a photograph of the M78 region obtained by E. Kreimer on Oct 22, 1966 on which McNeil's Nebula is seen at virtually the same brightness as at discovery (Mallas & Kreimer 1978). This offers the important insight that the current eruption of the illuminating star is not the first one. We here summarize what is known about this star prior to the appearance of the nebula. The star lies within the error ellipse ($45'' \times 7''$ at PA 88^o) of the IRAS source 05436–0007, which is detected only at 12 and 25 μm with fluxes of 0.53 and 1.19 Jy, respectively, with a flag that indicates an 80% probability that the fluxes are variable. The star also coincides with the 2MASS source 05461313–0006048, which is located at α_{2000}: $05^h46^m13.1^s$, and δ_{2000}: $-00^o06'05''$. The 2MASS photometry is listed in Table 1. A faint optical counterpart to this 2MASS source is visible on an I-band image

[2]This reference is listed as McNeil, Reipurth, & Meech (2004) in the Astrophysics Data System. The second and third authors only provided a simple confirmatory CCD image, and full credit for the important discovery of the eruption in IRAS 05436–0007 should go solely to Mr. McNeil. Consequently, we suggest that future reference to the discovery announcement in this IAU Circular be given as McNeil (2004).

obtained by Eislöffel & Mundt (1997). In the sub-millimeter, the source was detected as a compact, isolated dust continuum source at 350 and 1300 μm by Lis, Menten, & Zylka (1999), their source LMZ 12, a designation we will use for the source in the following until a variable star name is assigned in the GCVS. Subsequently, the same source was detected at 850 μm by Mitchell et al. (2001) and Johnstone et al. (2001), their source OriBsmm 55. Lis et al. (1999) suggested a pre-outburst bolometric luminosity for LMZ 12 of 2.7 $L_{\odot}$. These sub-millimeter observations additionally detected extended, diffuse emission about 40 arcsec north of LMZ 12, coinciding with part of McNeil's Nebula. Limited millimeter observations by Lis et al. (1999) did not reveal any molecular outflow from the source, and only a small core in HCO^{+}.

4. Observational Results

We present in Fig. 1 a color image of McNeil's Nebula based on g', r', and i' images taken with GMOS at the Gemini-N telescope in 0.5″ seeing. The nebula has approximate dimensions of 30 × 60 arcsec, and shows considerable structure, with a very bright patch of illumination near the source. Photometry of LMZ 12 at its apex is given in Table 1. Note that because of the bright nebulosity, the stellar magnitudes are very sensitive to the aperture-size employed, we used a small aperture of 0.9″ radius.

The nebula encompasses the Herbig-Haro object HH 22 (Herbig 1974). However, the detection of a collimated jet associated with HH 22 emanating from a source further to the East suggested to Eislöffel & Mundt (1997) that there is no connection between this HH object and LMZ 12. Another HH object, HH 23, is located further to the North. It consists of two knots on an axis that passes close to LMZ 12, and Eislöffel & Mundt (1997) suggested that the faint optical source coincident with LMZ 12 is the driving source. McNeil's Nebula opens up in the approximate direction towards HH 23, and we suggest that it represents the illuminated outflow cavity carved at some time in the past by LMZ 12 into the L1630 cloud. Proper motion measurements of HH 23 are needed to establish a firmer link with LMZ 12.

Infrared J, H, K′ photometry of the source obtained on Feb 03, 2004 is listed in Table 1. It is evident that the source is much brighter now than when the 2MASS data were obtained on Oct 07, 1998. At the time of our observations, LMZ 12 had brightened by ΔJ=3.6, ΔH=3.2, and ΔK′=2.9 magnitudes. When plotted in a J-H/H-K′ diagram, it is evident that it displays a substantial infrared excess (Fig. 2). It is noteworthy that in its current high state, LMZ 12 shows considerably *less* reddening than at the time of the 2MASS observation in 1998.

In Fig. 3 we show a contour diagram of LMZ 12 as seen in our K′-band images. It is immediately obvious that the star is surrounded by a compact reflection nebulosity and that, in particular, this nebula shows a curved tail characteristic of many stars undergoing high-accretion events (e.g., Herbig 1977). In Fig. 4, we show a K-band spectrum of LMZ 12, which displays a red continuum with strong CO-bandhead emission, and the Brγ and Na I lines are in emission. Our optical spectrum of LMZ 12 shows a red continuum with a prominent Hα line in emission, but no other emission or absorption lines, suggesting the presence of heavy veiling. The Hα line, shown in Fig. 5, has an equivalent width of −32 Å and displays a characteristic P Cygni profile. The absorption component has an equivalent width of 5.6 Å.

5. Discussion

The two major classes of eruptive variables among pre-main sequence stars are the FUors and the EXors (Herbig 1966, 1977, 1989). In the following we discuss whether LMZ 12 can be linked to one of these two categories.

FUors are characterized by large-amplitude (ΔV$\sim$5-6 mag.) brightenings lasting several or many decades, and in the optical they show F-G type spectra without emission lines. In the K-band region, FUors display deep CO-bandhead absorption (e.g., Reipurth & Aspin 1997). Although LMZ 12 has about the right amplitude, it remains to be seen how long it stays bright. Spectroscopically, however, LMZ 12 looks very different from mature FUors both in the optical and in the infrared. The prominent Hα emission and the strong CO emission that are presently seen do not suggest a classification as a FUor as we currently understand the phenomenon. On the other hand, Briceño et al. (2004) emphasize that the earliest optical spectrum after outburst of the FUor V1057 Cyg had some similarities to that of LMZ 12. Further photometric and spectroscopic monitoring of the star is required to settle this.

EXor eruptions, which may occur repeatedly in a given star, have amplitudes that can be comparable to those of FUors, but they have durations which are much shorter, from a few months to a few years. Spectroscopic studies of EXors are limited, because of the rarity and shorter durations of these eruptions. The few such studies that have been made (e.g., Lehmann, Reipurth, & Brandner 1995; Herbig et al. 2001; Parsamian et al. 2002) all show that EXors in eruption have at least the lower Balmer lines in emission, together with emission lines of He I and other lines characteristic of the most active T Tauri stars (Herbig 1962). A high-resolution spectrum of the Hα line of SVS 13 in outburst (Eislöffel et al. 1991) shows a P Cygni profile rather similar to the one seen in Fig. 5. However, we do not see any other emission lines than Hα in the spectral range observed (4800-6800 Å)

in LMZ 12. Infrared spectra of EXors are even more limited, one case is the eruption of SVS 13, for which a K-band spectrum shows the CO bandheads strongly in emission as well as Brγ in emission (Carr & Tokunaga 1992). However, a similar spectrum of EX Lup shows Brγ in emission, but the CO bandheads and Na I in absorption (Herbig et al. 2001). It thus does not seem that EXors have a unique infrared spectral signature. Based on a comparison with these somewhat limited observations of EXors, we conclude that LMZ 12 does have a certain resemblance to EXors.

The spectroscopic data give us some insight into the physical processes behind the observed eruption. The detection of Brγ in emission testifies to a region of hot gas. Brγ emission has been shown to correlate tightly with accretion luminosity, so its presence indicates that the eruption is linked to an episode of accretion (Najita et al. 1996; Muzerolle et al. 1998). The pronounced P Cygni profile seen at Hα in the optical spectrum is likely to be formed in a strong wind that has sufficient optical depth to produce the deep blueshifted absorption trough (e.g., Muzerolle et al. 2001). Only few T Tauri stars show such well-developed P Cygni profiles at Hα. The well-defined blue edge of the absorption trough indicates wind velocities of up to 600 km s^{-1}, even more than the extreme wind that emanates from FU Orionis (e.g., Herbig et al. 2003).

It is noteworthy that we see no spectral features indicative of shocks: the infrared spectrum shows no evidence for H_2 emission, and the optical spectrum does not display the [SII] 6717/6731 lines characteristic of Herbig-Haro jets. Our H_2 2.122 μm image of LMZ 12 shows no presence of any extended jet flow. It thus appears that LMZ 12, in common with most FUors and EXors, has powerful mass loss, but apparently not in the well-collimated fashion that enables shocked HH jets.

One final insight into the LMZ 12 EXor event comes from the changes of the infrared colors from before to after the eruption. The pre- and post-outburst colors show that LMZ 12 has moved precisely along a reddening vector, indicating that the star has brightened partly because its visual extinction diminished by about 4.5 magnitudes. Using the reddening curve of Rieke & Lebofsky (1985), we find that this corresponds to A_J=1.26, A_H=0.81, and A_K=0.50. Since we know that the infrared colors changed by ΔJ=3.64, ΔH=3.16, and ΔK=2.87, we see that the intrinsic brightening of the star corrected for the change in extinction is 2.4 magnitudes in each of the J, H, and K filters. Through a combination of this intrinsic brightening and the clearing away of an obscuring layer, the star has been able to illuminate its outflow channel, thus creating McNeil's Nebula.

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Table 1. Photometry of IRAS 05436–0007

Date	g'	r'	i'	J	H	K′	Telescope
Oct 7, 1998				14.74±.03	12.16±.03	10.27±.02	2MASS
Feb 03, 2004[a]				11.1±.1	9.0±.1	7.4±.1	Gemini
Feb 14, 2004[b]	22.8	17.4	15.6				Gemini

[a]We list large and conservative error estimates for the Gemini IR photometry, since this object is very bright for an 8m telescope, requiring very brief integrations.

[b]GMOS photometry is obtained in an aperture with radius 0.9″ in order to avoid bright nearby nebulosity. It is quoted to one decimal place only since we use standard zeropoints from the Gemini GMOS web site.

Fig. 1.— A color-image of McNeil's Nebula obtained by combining broadband g', r', and i' images obtained with GMOS at the Gemini-N 8m telescope. LMZ 12 is at the bottom of the nebula, and HH 22 is the bluish curved object on the northeastern edge of McNeil's Nebula. The height of the figure is about 80 arcsec. North is up and East is left.

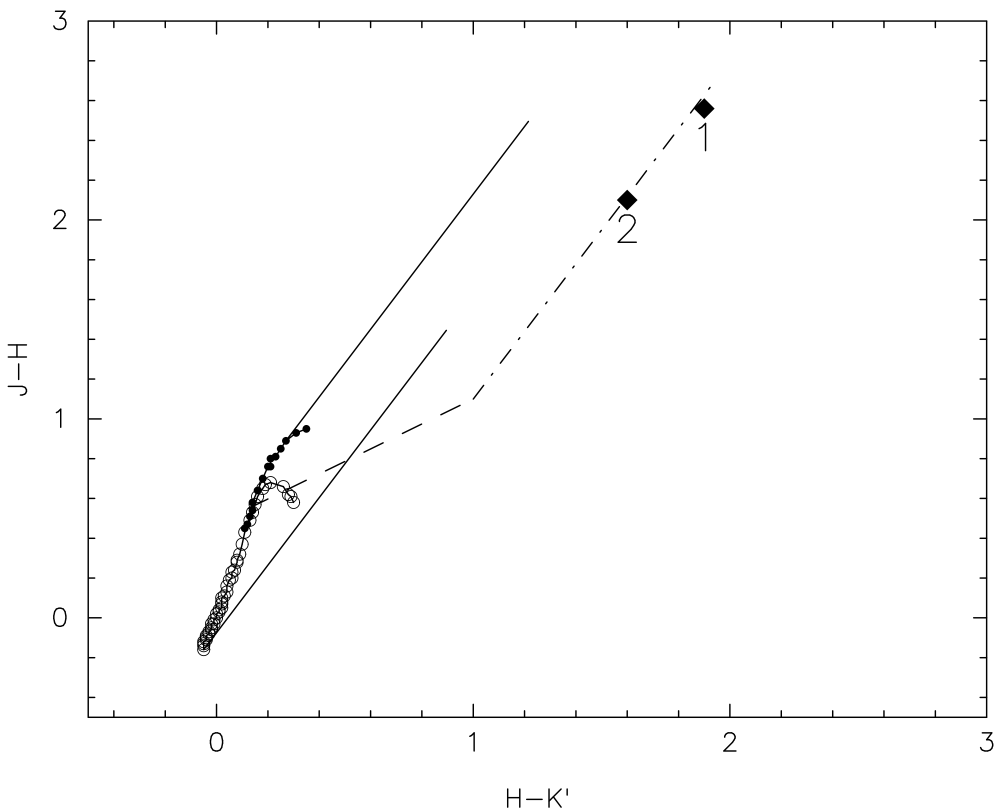

Fig. 2.— A J-H/H-K′ diagram showing the location of LMZ 12 as observed with 2MASS [1] on Oct 7, 1998 and with Gemini-N [2] on Feb 3, 2004. The dashed line is the T Tauri locus, and the solid straight lines and dot-dashed line are reddening vectors of A_V=15 mag.

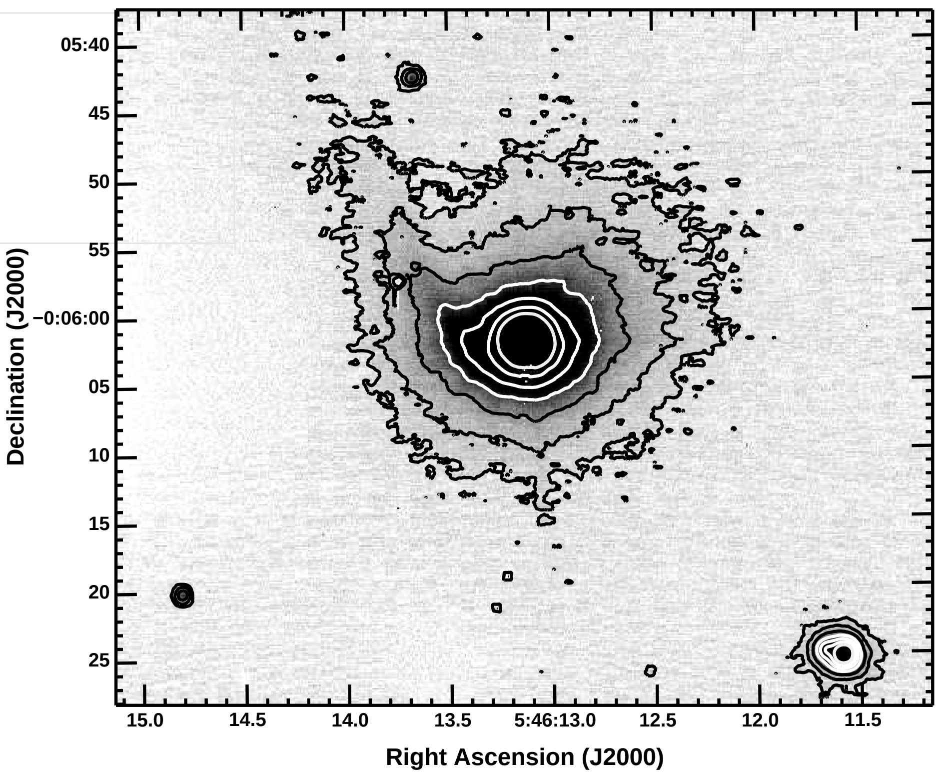

Fig. 3.— A compact nebula is seen around the illuminating star of McNeil's Nebula in this K′-band image obtained with NIRI at the Gemini-N 8m telescope.

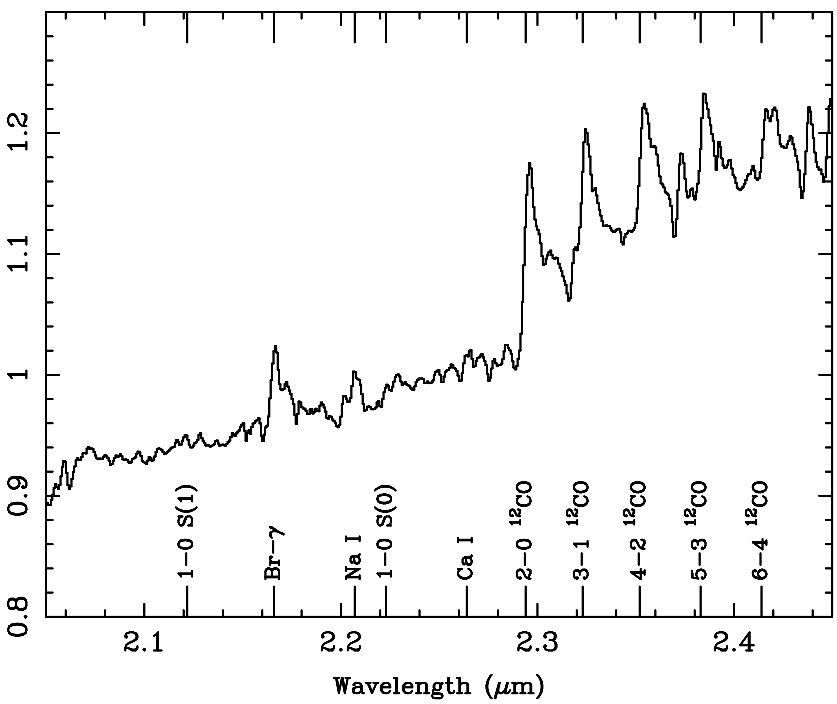

Fig. 4.— A K-band spectrum of LMZ 12 obtained with NIRI at the Gemini-N 8m telescope.

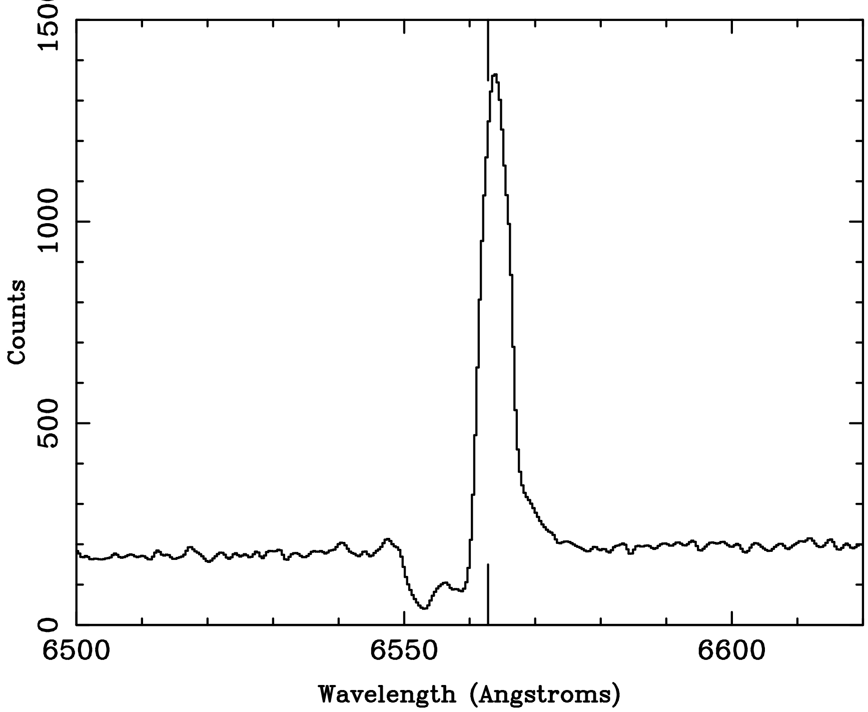

Fig. 5.— The Hα line in LMZ 12 shows a pronounced P Cygni profile. The rest velocity of the star is indicated.